Optics Recommendation

There are a couple of different ways to give a guideline or recommendation for optics especially a lens selection. The following description will give a support in decision for the right lens. There will be a short report about mounts and images sizes, magnification, focal length, f-number, and spectral ranges.

Mounts and Image Sizes

First of all we can separate between C-mount and F-mount flanges. C-Mount has a back flanges distance of 17.526 mm and a thread of 1 x 32 UN2A, F-Mount has a distance of 46.5 mm and typically the Nikon bayonet flange. C-Mount can be used for image diagonals up to 1”. Note, that this number does not have a direct relation to the real diagonal, it comes from the diameter of the old TV-tubes.

Image sizes: 1/3”: height: 3.6 mm, width: 4.8 mm, diagonal: 6.0 mm
1/2”: height: 4.8 mm, width: 6.4 mm, diagonal: 8.0 mm
2/3”: height: 6.6 mm, width: 8.8 mm, diagonal: 11.0 mm
1”: height: 9.6 mm, width: 12.8 mm, diagonal: 16.0 mm

To avoid vignetting the inner diameter of the lens tube (C-mount about 20 mm) should be larger than the diameter of the image. All this is valid for line scan cameras. For example a Basler 1k-line is 10.24 mm, a 2k-line is 20.48 mm, meaning a 1k-line can use a C-mount, for a 2k-line we recommend F-mount. There is a huge amount of different mounts, C- and F-mount are the most common ones, but V-mount, M42 x 1, M42 x 0.75 (called T2), and M39 x 1/26” are also used. In some case the flange focal distance is adapted to realize short focal lengths.

Magnification

Magnification β is calculated by $\beta = y'/y$, where y' is half the image size (for example 5.12 mm = ½ x 10.24 mm for a 1k-line) and y is half the size of the object. Note, that full size image divided by full size object is as well the magnification. The ratio of the distance from the object to the lens a and the distance from the lens to the image a' gives the magnification β, too.

Focal Length

The focal length f' (mostly the same as *f, too*) of a lens is calculated by different ways, having the wanted magnification and the object distance: $f' = a / (1+(1/ \beta))$ or $f' = a / (1+(y/ y'))$. The basic equation is $f' = 1 / (1/a + 1/ a')$. The focal length is usually calculated with the help of these formulas, then you have to check the closest focal length, which is offered. Note, that the labeled number is not the real focal length (a 35 mm lens could have a focal length of 33.78 mm). This might change your field of view (FOV). Use the following equation for the change in object size to compare with the wanted object size: $y = y' \times (a/f' - 1)$, with y half of the object size, y' half of the images size, a object distance, and f' focal length. Note, the equation is valid for y and y' for full sizes, too.

F-Number (*F/#*) and Diffraction Limit.

The F-number (*F/#*) gives a number for the amount of light that is able to travel through the lens. It is calculated by $F/\# = f'/d$, with f' as focal length and d as diameter of the aperture (roughly(!) the size of the lens itself). F-numbers often are *22, 16, 11, 8, 5.6, 4, 2.8, 2,* and *1.4*. They always change by a factor of sqrt(2), meaning a factor 2 in intensity. The lower the F-number is the more light can travel through the lens, but as well the aberration will increase. Best image results will appear with $F/\# = 4, 5.6, 8$. With lower F-numbers the images is blurred by aberrations (spherical aberrations, astigmatism, field curvature, coma, distortion, and chromatic aberrations) for high f-numbers it is blurred by diffraction. The diffraction limit is given by the diameter of the Airy-disk: $Ø_{Airy} = 2.44 \times \lambda \times F/\#$, with λ for the (average) wavelength. As a rule of thumb, the limit for visible light is roughly the F-number in microns. This is in the same range as the size of the pixels (e. g. 6.7 µm for the Basler A101).

Spectral Ranges

Basler cameras cover a spectral range from 400 to 1000 nm. This is a more than the human eye is able to detect (roughly 400 to 800 nm). Color cameras usually have a Bayer pattern (see manuals for a sketch) in front of the CCD chip. Note, that the effective resolution of the chip has to be divided by two in each direction. The blue channel is sensitive from 400 to 500 nm, the green from 500 to 600 nm, and the red for more than 600 nm. Unfortunately the near infrared (NIR) opens for all three channels. To avoid wrong colors, (e. g. greens leaves) a IR-cut filter is used. For C-Mount cameras it could be mounted in front of the CCD. Some lenses are corrected for the visible range, some include the NIR.

Choice of Lenses

A lens (or better an objective containing several lenses) is always designed for certain parameters. It is always a compromise between magnification, FOV, F/#, spectral range, image size, aberrations, and finally costs.

If possible, avoid zoom lenses for two reasons: First, zoom lenses have to make larger compromises than fixed focus ones. Second, usually they are moved by a small motor inside a normal (photo-) camera. Tolerances are much higher in order to use motors with less power.

Autoiris usually makes no sense, because exposure times can be handled electronically by shutter times. Changing the iris varies the depth of focus (DOF). Thumb rule for visible light: $DOF = \pm (pixel\ size) \times F/\#$.

Next point to select is the magnification. Normal lenses have the best images for $\beta = 1{:}infinity$ to $1{:}10$. This is usually restricted by the minimum optical distance (MOD). For sure, with rings between the lens and the mount you are able to change the magnification, but the lens is not designed for that magnification, the image may be blurred! For good images do not use those rings! For machine vision magnifications $\beta = 1{:}20$ to $1{:}2$ are mostly used. Normal macro lenses cover a range from $\beta = 1{:}4$ to $1{:}1$. For enlarging, meaning the image is larger than the object, $\beta = 1{:}1$ to $4{:}1$ use macro lenses in reverse orientation. Note, that there is enough space for mounting the lenses. Normally they have special mounts. For magnifications $\beta \geq 5$ use microscopic lenses. Note, that normal microscopic lenses will have a maximum image of a 2/3” chip. A magnification of 10 will work, but a 20x will have two limitations. First, usually the working distance is very small. Use bright light illumination in reflection or transmission if possible. Second, a pixel size of 6.7 µm will correlate to an object size of 0.34 µm. This is less than the wavelength of the visible light. Under normal conditions this makes no sense. A necessary point is a huge aperture, meaning a very low F/#. The DOF is very small (a few hundreds of a millimeter), alignment is not easy, but nearly impossible for line scan cameras (maximum 1k-line). It is strongly recommended to avoid line scan cameras with microscopic lenses.

Telecentric lenses have two great advantages: First, the image is free of perspective, second, the DOF is rather large. This is done with a lens between the object and the lens in front of the camera. The lens has to be at least as large as the object which should be inspected. This makes is usually very expensive. The lens produces a virtual image (compared to a magnification lens for the human eye) and changes distance and aperture (or F-number).

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